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FLEXIBLE MATERIALS TECHNOLOGY

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OBJECTIVES

The study program was focused at four major objectives as follows:

First, an identification of flexible components -- specific components for Phase II systems and typical components for a wide spectrum of potential large space systems, including Phase I systems.

Second, the definition of the material requirements for the identified flexible components in terms of material types, forms and typical or critical properties, and the generation of applicable materials data for near-term systems.

Third, the assessment of the interrelation between the characteristics of flexible materials and systems performance. This was to be demonstrated in quantitative terms for specific designs and materials of large deployable antennas.

The ultimate objective of the study was the identification of advanced material concepts and the formulation of a plan for the required materials Research and Development.

OBJECTIVES

IDENTIFICATION OF TYPICAL FLEXIBLE MATERIALS

- SYSTEMS APPLICATIONS
- EMPHASIS ON DEPLOYABLE ANTENNAS

TYPICAL/CRITICAL MATERIAL CHARACTERISTICS

MATERIAL TYPES, FORMS, CAPABILITIES

- REQUIRED - ACTUAL

SYSTEMS PERFORMANCE OF FLEX MATERIALS

- FAILURE ANALYSIS
- PERFORMANCE PREDICTION

POTENTIAL ADVANCEMENTS

MATERIALS TECHNOLOGY DEVELOPMENT PLAN

ACCOMPLISHMENTS

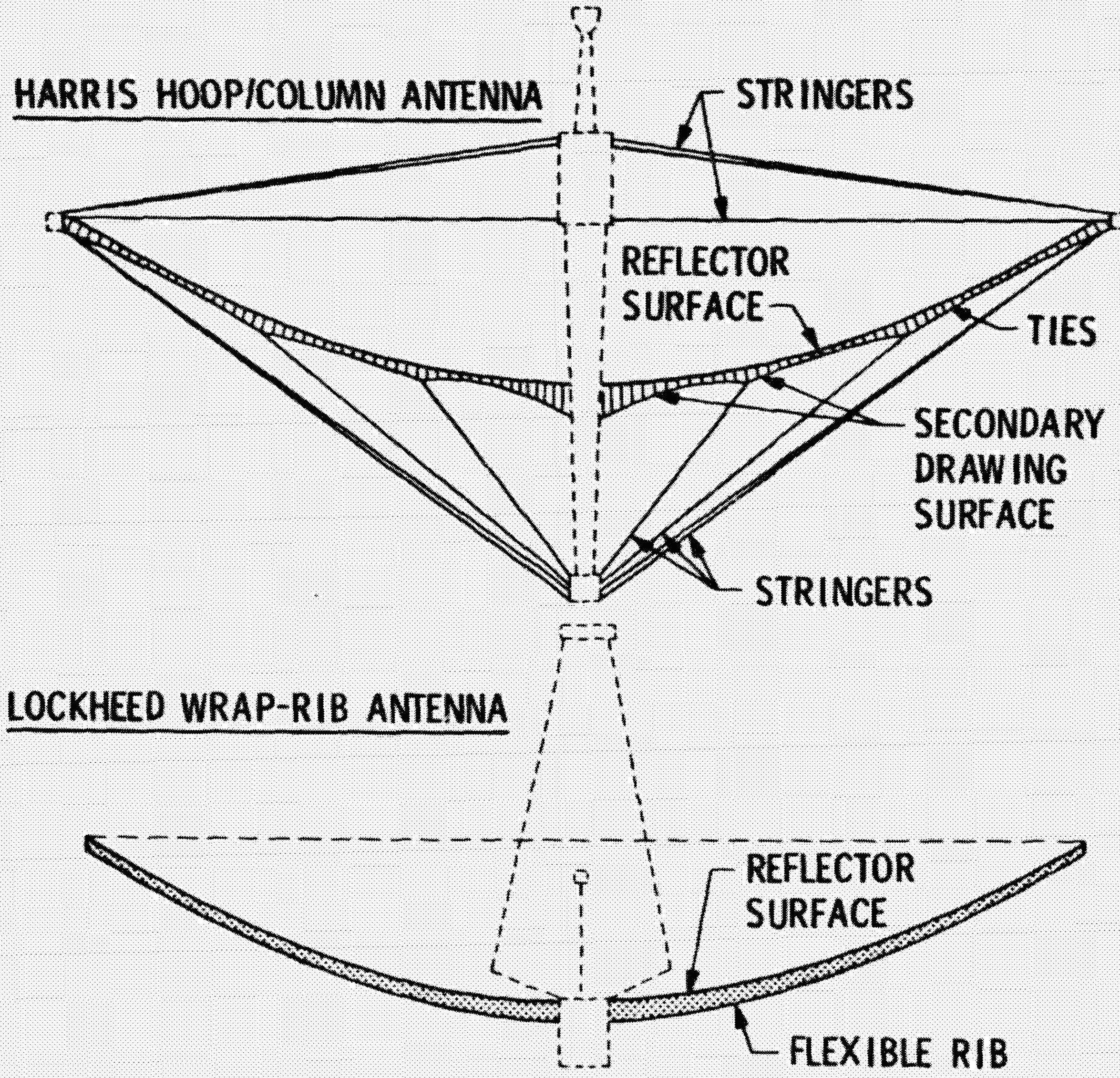
A survey of all presently defined or proposed large space systems indicated an ever-increasing demand for flexible components and materials, primarily as a result of the widening disparity between the stowage space of launch vehicles and the size of advanced systems. Typical flexible components and material requirements were identified on the basis of recurrence and/or functional commonality. This was followed by the evaluation of candidate materials and the search for material capabilities which promise to satisfy the postulated requirements. Particular attention was placed on thin films, and on the requirements of deployable antennas. The assessment of the performance of specific materials was based primarily on the failure mode, derived from a detailed failure analysis. In view of extensive ongoing work on thermal and environmental degradation effects, prime emphasis was placed on the assessment of the performance loss by meteoroid damage. Quantitative data were generated for tension members and antenna reflector materials. A methodology was developed for the representation of the overall materials performance as related to systems service life. A number of promising new concepts for flexible materials were identified. Work on a proposed materials R & D plan is still in progress.

ACCOMPLISHMENTS

- TYPICAL FLEXIBLE MATERIALS, APPLICATIONS AND REQUIREMENTS IDENTIFIED
- MATERIALS EVALUATED
  - PROPERTIES
  - THIN FILMS
  - DEPLOYABLE ANTENNAS
- SYSTEMS PERFORMANCE ANALYZED
  - SYSTEMS REQUIREMENTS, ENVIRONMENTS
  - FAILURE MODES
  - PERFORMANCE PREDICTION
  - EMPHASIS ON METEOROID HAZARD
- POTENTIAL ADVANCEMENTS IDENTIFIED
- R&D PLAN IN PREPARATION

The purpose of this figure of two deployable antennas is to illustrate the extensive use of flexible materials in large space systems. Flexible components are identified by bold lines and rigid components by dotted lines. Note the predominance of flexible materials.

FLEXIBLE COMPONENTS OF DEPLOYABLE SPACE ANTENNAE



TYPICAL FLEXIBLE COMPONENTS AND MATERIALS

There is a wide variety of flexible components with an equal variety of forms and material types. The fundamental requirement of all flexible components is a purely elastic material deformation in stowed condition. Most widely used are membranes, meshes or fabrics for large reflective surfaces (RF, light etc.) and cables, tapes or single filaments for tension members. Both applications involve <u>thin</u> materials in the form of films or wires (fibers) to preclude any plastic deformation during stowage. The only flexible component with substantial wall thickness is, at least at present, the wrap-rib; it is, however, also only elastically deformed in stowed conditions. In the case of extendible booms and vanes, both the surface material (film, fabric) and the supporting structural elements are stowed elastically. The use of metal foil for deployable drag shields calls for a controlled stowage configuration (wave pattern between ribs) to assure purely elastic deformation.

TYPICAL FLEXIBLE COMPONENTS AND MATERIALS

COMPONENTS	FORMS	MATERIALS
REFLECTOR SURFACES	KNIT MESH WEAVE MESH MEMBRANES	COATED METAL WIRE METALLIZED POLYMER YARN METALLIZED POLYMER FILM
TENSION MEMBERS STAYS STRINGERS TIES	CABLES CORDS TAPES WIRES	DIELECTRIC COMPOSITES SILICA, POLYMERS GRAPHITE FIBER COMPOSITES INVAR WIRE
FLEXIBLE RIBS	LOW CTE LAY-UP COMPOSITES	GRAPHITE/POLYMER GRAPHITE/AL OR MG
FLEXIBLE JOINTS	"CARPENTER TAPE" ELASTIC HINGES	SPRING METAL FOIL
EXTENDIBLE BOOMS	THIN-WALL CYLINDERS	REINFORCED THIN FILMS WIRE GRIDS
STATION KEEPING VANES	TENSIONED MEMBRANES ELASTIC FRAMES	METALLIZED POLYMER FILM GRAPHITE FIBER COMPOSITE
DRAG SHIELDS	METAL FOIL	NI-BASE SUPER ALLOYS

FLEXIBLE MATERIAL PROPERTIES

In the definition of material requirements and capabilities a distinction is made between basic and specific properties. Basic properties are those which apply to flexible materials for space structures in general, such as flexibility for stowage and deployment, or dimensional stability and resistance to space environments in service. Some components call for additional material capabilities, designated as specific properties.

Emphasis was placed on thermal properties (thermal expansion, conductivity, cycling), creep (particularly applicable to polymers), optical surface properties, environmental materials degradation and failure due to meteoroid impact. It was attempted to relate all properties to their individual or collective effect upon systems performance and useful service life.

REQUIRED MATERIAL PROPERTIES

BASIC PROPERTIES

- FLEXIBILITY (ELASTICITY)
  - STOWAGE
  - DEPLOYMENT
- DIMENSIONAL STABILITY
  - LOW THERMAL EXPANSION
  - LOW PLASTIC DEFORMATION
  - NO CREEP
- LOW DENSITY
- OPTICAL SURF. PROPERTIES
- RESISTANCE TO SPACE ENVIRONMENT
  - VACUUM
  - UV AND HIGH ENERGY RADIATION
  - MICROMETEOROID IMPACT

ADDITIONAL SPECIFIC PROPERTIES

REFLECTOR SURFACES
- ADAPTABILITY TO METALLIC COATING (Ag, Au)
- SURFACE INTEGRITY DURING STOWAGE

TENSION MEMBERS
- HIGH STRENGTH
- HIGH MODULUS
- HIGH ELASTIC RANGE

FLEX RIBS
- HIGH STIFFNESS AS DEPLOYED
- ADEQUATE THERMAL CONDUCTIVITY

FLEX JOINTS
- HIGH ELASTIC MODULUS AND RANGE

THIN FILM APPLICATIONS

Thin film applications comprise active functions (RF reflectors, light reflectors, drag shields), primary structural functions (extensible booms, inflatable systems) or structural support functions (solar array substrate). With the exception of the drag shield where high temperatures call for metal foil, all applications involve polymer films, either plain, metallized or reinforced. For antenna reflectors in the GHz regime the usefulness of polymer films is questionable, even with active shape control, due to progressive plastic deformation. Self-rigidizing films appear to have considerable potential; they are, however, completely undeveloped.

THIN FILM APPLICATIONS

APPLICATIONS	SPACE	ENERGY	FILM MATERIAL	R&D	ENGG.
ANTENNA REFLECTORS	●		METALLIZED POLYMER	√	√
SOLAR ARRAY SUBSTRATE	●	●	POLYMERS	√	√
" – CONCENTRATORS	●	●	METALLIZED POLYMER	√	√
SOLAR REFLECTORS - FLAT	●	●	"	√	
SOLAR CONCENTRATORS	●	●	"	√	√
EXTENDABLE BOOMS	●		REINFORCED POLYMERS	√	
SOLAR SAIL / VANES	●		METALLIZED POLYMER	√	√
ENV. SHIELDS, ENCLOSURES	●		"	√	
DRAG SHIELDS (AEROBRAKE)	●		METAL FOIL	√	√
GAS FILLED LENSES	●		POLYMERS	√	
INFLATABLE STRUCTURES	●	(●)	"	√	
" – RIGIDIZED	●	(●)	SELF-RIGIDIZING POLYM.	√	

PROPERTIES OF POLYMER FILMS

The most important property of thin films for space applications is the resistance to high-energy radiation; the materials in the chart are, therefore, arranged in the order of decreasing radiation threshold value (with the exception of parylene placed at the bottom as it is unstable in air, yet stable at synchronous altitude). Some polymers, such as epoxies or polystyrene, are even more resistant, but not available as films.

The effectiveness of a film material depends on the specific application. Most cases call for a combination of low environmental degradation, low thermal expansion, reasonably low density and reasonably high strength and temperature stability. In this combination of requirements, polyimide outranks all other film materials.

PROPERTIES OF POLYMER FILMS

	CTE 10^{-5}	ρ g/cc	F_{tu} ksi	M_T ksi	TEMP. ^oC	RAD 10^X
POLYIMIDE (KAPTON)	2.5	1.42	25	430	350	8.5-9.5
MYLAR	5.3	1.38	25	550	150	6.5-7.5
POLYCARB. (LEXAN)	3.8	1.20	9	290	135	6.5-7.5
TEFLON FEP	8-10	2.15	3	70	200	5-6
TEFLON PFA	7-11	2.15	7	70	260	5-6
POLYSULFONE	3.1	1.24	12	450	150	5-6
PARYLENE*	3.5	1.12	7		350	9

*NOT STABLE IN AIR

COMPARISON OF ANTENNA MESH MATERIALS

This chart is designed to convey an overview of the merits of typical antenna mesh materials. It compares the two predominantly used materials, molybdenum wire and polymer yarn, with the potential advanced materials, graphite yarn, and with plain silver wire as reference. The significant properties are electrical resistance, thermal expansion and density. As all materials are coated with silver or gold, they exhibit the same electrical surface properties. The added significance of the coefficient of thermal expansion is reflected in the merit function 1/R (silver wire = unity). The superiority of molybdenum wire over polymer yarn is reversed if we also account for mesh weight (merit function 1/Rα).

Even though graphite yarn mesh is not yet available, the extremely high merit values make a strong case for a development effort.

COMPARISON OF ANTENNA MESH MATERIALS

WIRE OR YARN	COATING	RESIST. R $\mu\Omega$cm	CTE $10^{-6}/^{o}C$	DENS. ρ g/cc	MERIT FUNCTIONS $\frac{1}{R}$	$\frac{1}{R\alpha}$	$\frac{1}{R\alpha\rho}$
SILVER WIRE	—	1.47	19.6	10.5	1	1	1
MOLYBDENUM WIRE	SILVER	1.6	6.3	10.2	0.92	2.85	2.94
	GOLD	2.4		10.5	0.62	1.90	1.90
POLYESTER YARN	SILVER	1.6	22	1.6	0.92	0.81	5.3
	GOLD	2.4		1.9	0.62	0.52	2.8
GRAPHITE YARN	SILVER	1.6	1.0	2.4	0.92	18.0	78.5
	GOLD	2.4		3.2	0.62	12.0	39.4

FAILURE MODES

There are essentially two basic modes of material-induced systems failure: (1) loss of systems performance and (2) catastrophic failure.

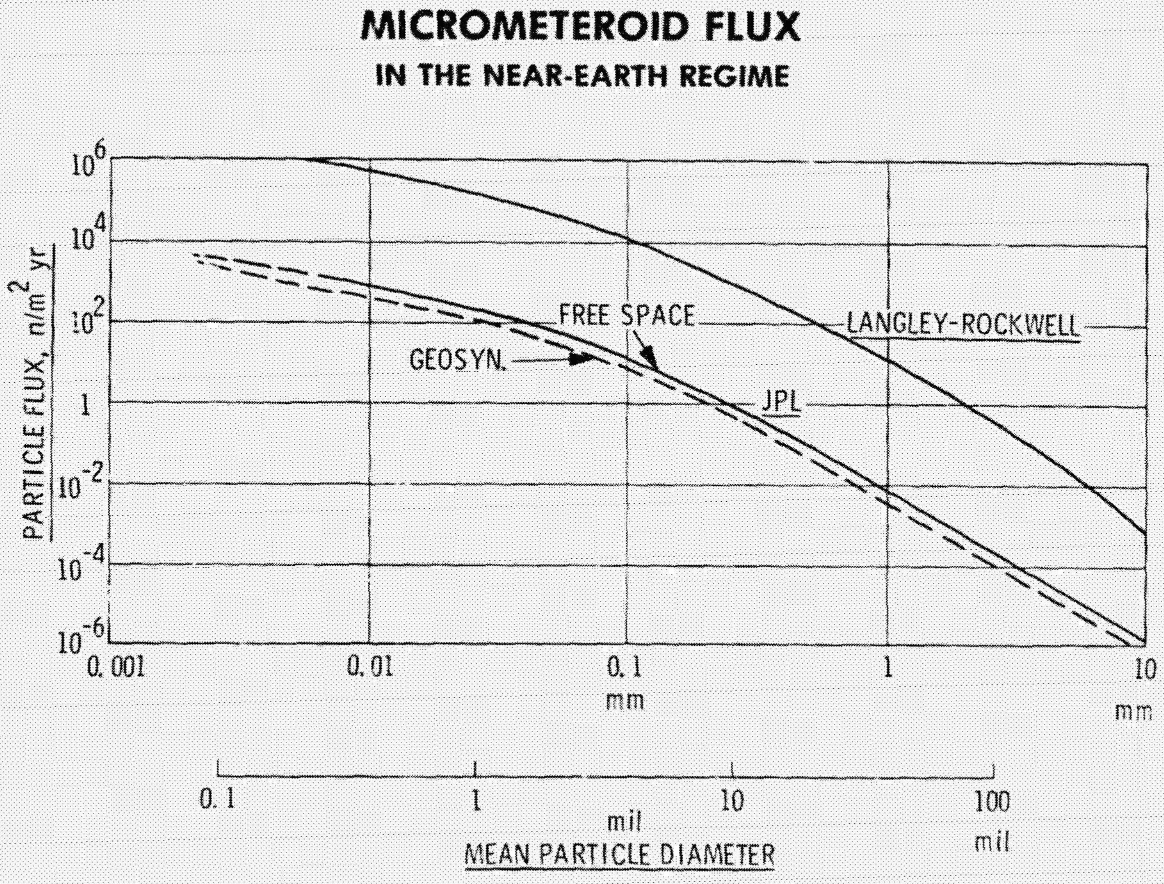
Loss of systems performance may occur as the result of repetitive transient effects, such as excessive thermally or load-induced deformations; this may be avoided by proper design and accurate materials data. Gradual performance loss due to intrinsic material characteristics and environmental effects, in contrast, is unavoidable and has to be taken in account in the prediction of systems performance over the specified systems life. This places emphasis on the consideration of such time-dependent material characteristics as creep, internal (molecular) changes, environmental degradation and meteoroid damage.

Catastrophic failure may occur by either of two modes: (1) complete environmental material degradation due to high solar activity or unknown long-term effects, or both; (2) unexpected meteoroid rupture of several redundant tension members. Since both effects are unpredictable, they cannot be included in failure analyses and performance predictions. This is acceptable in view of the very low risk.

FAILURE MODES

LOSS OF SYSTEMS PERFORMANCE	SoA
EXCESSIVE STRUCT LOADS/DEFORMATION	●
EXCESSIVE THERMAL EXPANSION	●
CREEP	○
INTERNAL MATERIAL CHANGES	●
ENVIRONMENTAL DEGRADATION	●
PROGRESSIVE METEOROID DAMAGE	(–)
CATASTROPHIC	
ENVIRONMENTAL DEGRADATION	●
METEOROID IMPACT FRACTURE	(–)

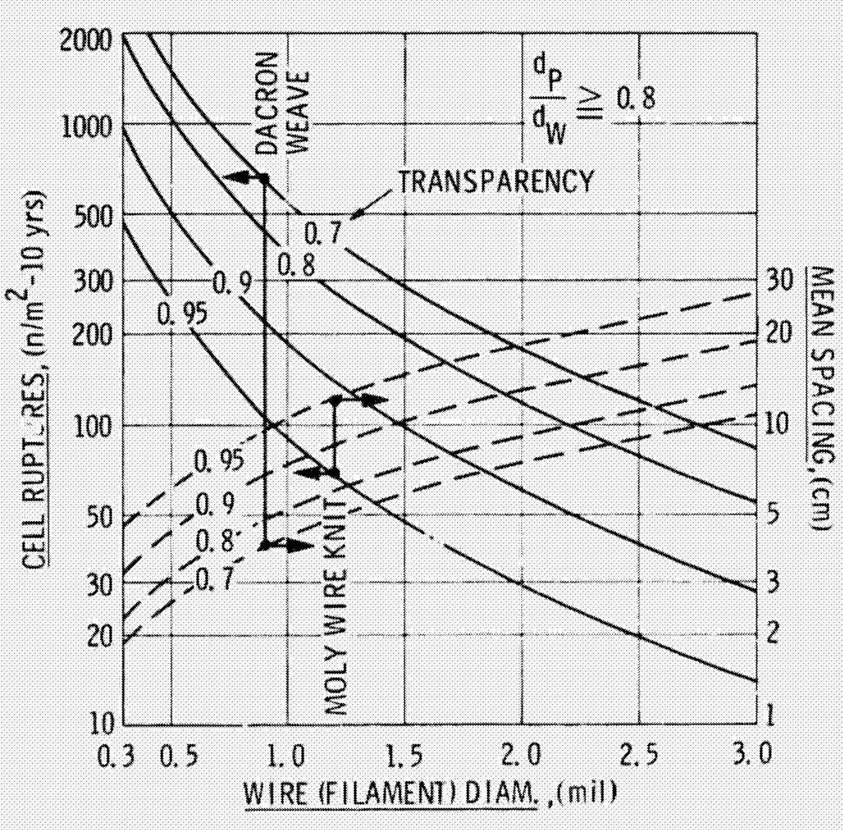
The meteoroid flux model, below, served as basis for the assessment of the gradual loss of performance due to meteoroid damage. It identifies the number of hits per m^2 and year by particles greater than the "mean particle diameter" for (1) "free" space (solid line) and (2) geosynchronous altitude (dotted line) accounting for the earth body-shielding and de-focusing effects. In this evaluation, the "JPL" data are used with confidence, as they have been derived from satellite measurements and have been successfully used in the design of JPL missions for years. The curve marked "Langley-Rockwell" represents flux data from the "Preliminary Handbook of Near Earth Environments," April 1979 (unpublished) which differ from the JPL data by almost 3 orders of magnitude.



The degree of damage due to exposure to the meteoroid environment is determined by the number of ruptures expected within a given exposure time. For mesh reflector materials, the smallest meteoroid particle which causes rupture is dependent on the filament (wire) diameter and defined by the ratio d_p/d_w of min. particle diameter to filament diameter. For reflector meshes, a conservative value of 0.8 has been adopted, which accounts for some redundancy of the invariably multifilar base materials. The susceptible surface area, further, is determined by the mesh transparency.

The chart below identifies the expected meteoroid damage to mesh reflectors over a 10-year period. For a given filament or wire diameter and a given transparency the diagram permits the determination of the number of cell ruptures per m^2 (in 10 years) and the mean spacing of these ruptures which, in turn, serves as basis for the prediction of the resulting surface deformation.

METEOROID DAMAGE TO MESH REFLECTORS



Progressive deformation ("sagging") of the reflector surface starts as soon as the cumulative local cell deformations (stretching) due to meteoroid-induced ruptures exceed the elastic deformation due to mesh preload tension (Elastic Limit "e"). As illustrated in the diagram below, this point can be expressed in years of service. For the selected example of a molybdenum wire knit with a wire diameter of 1.2 mils and 25 cells per inch (cell size 1 mm) and an elastic preload deformation of 1%, excessive surface deformation starts after 14.7 years of service.

As shown by the relationships, the surface deformation and time to failure are determined by the following terms: (1) mean rupture spacing at time t, derived from the number of ruptures per year and mesh transparency; (2) local rupture deformation as related to cell size; (3) linear elastic preload (lbs/in); (4) linear elastic modulus (lbs/in) and; (5) Poissons ratio of the mesh.

REFLECTOR DEFORMATION DUE TO METEOROID DAMAGE

$$\Delta\epsilon = \frac{\text{LOCAL DEFORMATION}}{\text{RUPTURE SPACING}}$$

$$= c\,\nu\,\sqrt{n \cdot t \cdot (1-T)} \quad (\text{m/m})$$

- c CELL SIZE (m)
- ν POISSONS RATIO
- n DAMAGING PARTICLES/m^2 yr
- t EXPOSURE TIME (yrs)
- T TRANSPARENCY

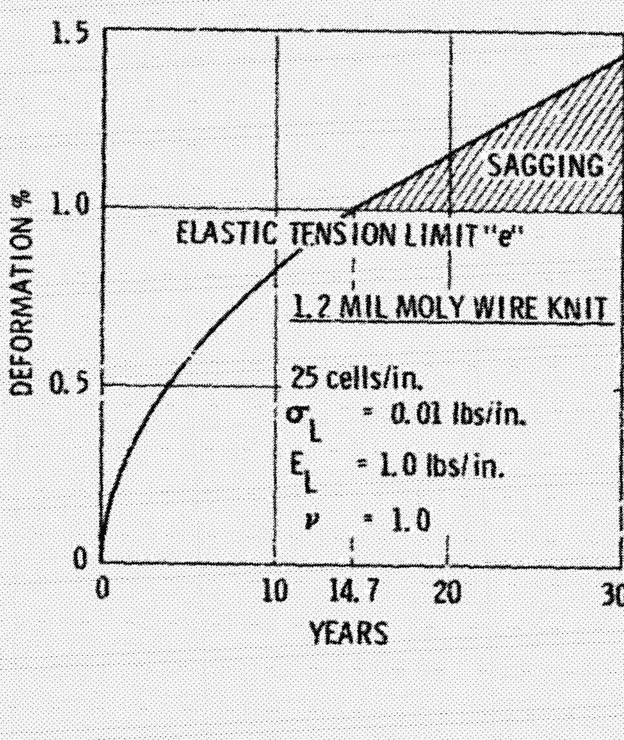
$$t_{FAIL} = \frac{e^2}{(c\nu)^2 \cdot n \cdot (1-T)} \quad (\text{yrs})$$

e ELASTIC LIMIT (m/m)

OR

$$t_{FAIL} = \frac{\sigma_L^2}{(E_L\, c\,\nu)^2 \cdot n \cdot (1-T)} \quad (\text{yrs})$$

- σ_L LINEAR TENSION (N/m)
- E_L LINEAR MODULUS (N/m)



COMPARISON OF REFLECTOR MATERIALS

The table below is designed to convey an overview of the merits and shortcomings of four typical antenna reflector materials by means of approximate data for atmospheric and solar light pressure, deformation resulting from thermal and micrometeoroid environments, total mass and stowability. All data are based on a reflector diameter of 100m and a 10-year service life.

The molybdenum wire knit exhibits the most favorable combination of properties; its only shortcoming is the high sensitivity to meteoroid damage, leading to substantial deformation. While the welded wire mesh is fairly resistant to meteoroid damage and thermal deformation, it exhibits poor stowability. A thin film reflector offers the advantage of meteoroid insensitivity, low weight and unparalleled stowability; this is offset by a poor thermal deformation resistance and an appreciable drag force due to solar light pressure. The Dacron weave mesh exhibits the most unfavorable combination of properties.

Omitted in this comparison is the resistance to degradation (UV, high energy radiation) since it is partially reflected in the thermal deformation properties. It tends to shift the emphasis again toward metallic mesh materials.

COMPARISON OF REFLECTOR MATERIALS

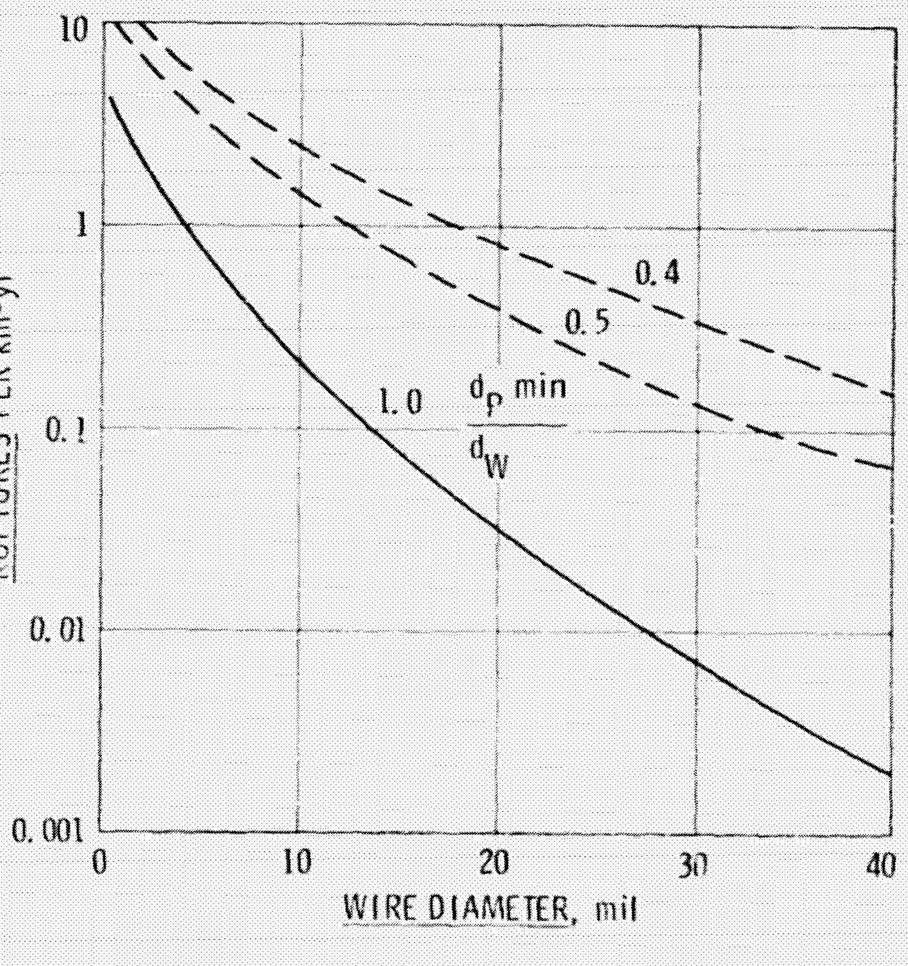
• REFLECTOR DIAM. 100 m • SERVICE LIFE 10 YEARS		MO KNIT MESH	MO WELDED MESH	DACRON WEAVE MESH	POLY-IMIDE FILM
THICKNESS (WIRE, FILAM., FILM)	mil	1.2	1.8	0.9	0.3
CELL COUNT	n/in.	25 x 50	25 x 25	25 x 25	0
TRANSPARENCY	%	95	90	70	0
MAX. ATMOSPH. PRESS.	g	0.014	0.011	0.036	0.12
SOLAR LIGHT PRESSURE	g	0.84	0.67	2.02	6.75
THERMAL DEFORMATN.	%	0	0.2	0.5	0.8
TOTAL CREEP	%	< 0.1	0.2	1.0	0.5
DAMAGING METEOR. HITS/m^2		68	72	660	4.2
– DEFORMATION	%	0.8	< 0.1	2.1	0
TOTAL SURFACE MASS	kg	289	326	218	96
STOWABILITY		Good	Poor	Good	Excell.

FAILURE OF WIRES/CORDS DUE TO
METEOROID IMPACT

In contrast to reflectors, the highly stressed condition of tension members is more sensitive to meteoroid impact, reflected in a smaller damaging particle size. The diagram identifies the number of expected ruptures per km length and year for tension members with circular cross-section (wires, cords, cables), as related to wire diameter and relative minimum damaging particle size (d_p/d_w).

While meteoroid damage in reflector surfaces produces a gradual loss of dimensional accuracy and performance, the rupture of a tension member may well be catastrophic, particularly at strategic locations. This places emphasis on a high degree of redundancy, either by appropriate material systems or design measures.

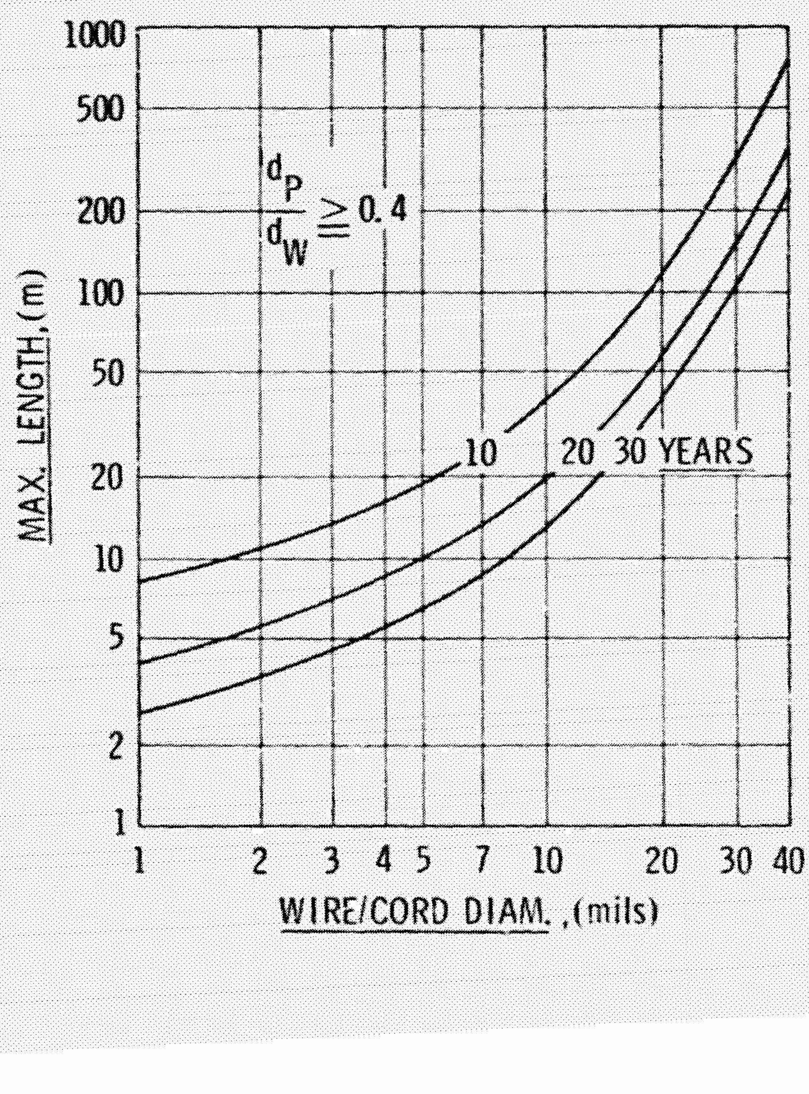
FAILURE OF WIRES/CORDS DUE TO METEOROID IMPACT



Even though tension members in the form of wires or stranded filaments represent only a small surface area, potential meteoroid encounter has quite severe consequences since the fracture of a single tension element in a strategic position may cause substantial deformation over a large part of the reflector surface.

The chart below identifies the maximum length of a tension member which may be considered as "safe", representing an extremely low probability of meteoroid induced fracture. For tension members, a low ratio of critical particle diameter to wire (cord) diameter has been applied ($d_p/d_w = 0.4$) in view of the stressed condition and the absence of redundancy.

MAX SAFE LENGTH OF TENSION MEMBERS
TO PREVENT RUPTURE BY METEOROIDS



MATERIAL PERFORMANCE PREDICTION

It was attempted to develop a methodology for the prediction and comparison of the overall materials performance in a large space system. The adopted concept is best illustrated by the example of excessive deformation as systems failure criterion, as it applies to high-gain reflectors. For a given material, the total deformation is composed of a constant value due to sustained effects, repetitive maxima due to transient (cyclic) effects, and a steadily increasing deformation value due to time-dependent materials characteristics as outlined in the chart at right. Since the total deformation or sum of these values contains a time-dependent term, it is equally time-related and permits the determination of the time at which it starts to exceed the maximum allowable deformation e_{LIM} postulated by systems performance. A very useful single value for the comparison of materials performance is the ratio of this time limit and the specified systems service life, designated as "Material Confidence Level". This value should in any case be greater than 1.0. Extremely high values indicate the potential of design relaxation.

MATERIAL PERFORMANCE PREDICTION

<u>TIME DEPENDENT EFFECTS</u>

CREEP
MOLECULAR CHANGES
METEOROID IMPACT
ENVIRONMENTAL DEGRADATION

de/dt

$$\Sigma e_{max} + t \frac{de}{dt} \leq e_{LIM}.$$

$$t_{LIM} = \frac{e_{LIM} - e_{max}}{de/dt}$$

<u>TRANSIENT EFFECTS</u>

THERMAL EXPANSION
CONTROL LOADS
INDUCED STRUCTURAL LOADS

e_{max}

<u>MATERIAL CONFIDENCE LEVEL:</u>

$$L_C = \frac{t_{LIM}}{t_{SERV}}$$

<u>SUSTAINED EFFECTS</u>

STRUCTURAL PRE-LOADS
ATMOSPHERIC DRAG
SOLAR LIGHT PRESSURE

POSTULATED: $L_C > 1.0$

In the course of the study, a number of promising advanced concepts for flexible materials or material systems were identified. Of particular interest are unidirectional composite tapes and multifilar material systems for tension members of high redundancy, polymer film-based graphite mesh for reflectors of high dimensional stability and inflatable/self-rigidizing polymer-base materials for a variety of structural applications (booms, hoops or even reflectors). These advanced material concepts are presently integrated in the proposed R & D plan.

POTENTIAL ADVANCEMENTS

- REDUNDANT TENSION MEMBERS (MULTIFILAR)
- COMPOSITE TAPES IN LIEU OF STRINGS
- GRAPHITE YARN MESH (REFLECTORS)
- THIN FILMS/ELECTROSTATIC SHAPE CONTROL
- MG/GRAPHITE COMPOSITES FOR FLEX RIBS
- FLEX JOINTS IN LIEU OF HINGES
- INFLATABLE SYSTEMS
- SELF-RIGIDIZING FLEXIBLE MATERIALS
  - STRUCTURAL COMPONENTS
  - REFLECTORS
- IMPROVED METHODOLOGY FOR MATERIALS PERFORMANCE PREDICTION